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Recycling of Waste Glass Powder and Tyre Fiber in the Development of Eco-Efficient Concrete for High-Performance Structural Application

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Abstract

Concrete suffers from several drawbacks due to the pollution associated with cement production, low tensile strength and low strain capacity that result in low resistance to cracks. Several attempts have been made to utilize waste materials for economical, sustainable construction and to improve concrete characteristics. This paper aims to investigate the effect of waste glass powder (WGP) as a partial replacement of cement and waste tyre fibre (WTF) as fibre reinforcement in the production of high performance concrete (HPC). ACI 211.1 was used to design a grade 50 HPC. At the first stage, WGP was introduced at a replacement level of 0 to 25 at a 5% interval by weight of OPC increment. Compressive strength at 3, 7, 28, 56, and 90 days of curing and slump flow was investigated, as well as establishing the optimum WGP content. WTF was then added to the optimal WGP-HPC in varying percentage addition of 0 to 2% at an increase of 0.4% by weight in the second stage. The compressive, splitting tensile, and flexural strengths at 3, 7, 28, 56, and 90 days were investigated. Slump flow was also investigated. It was discovered that the WGP is a suitable material for use as a pozzolana as it satisfied the minimum requirement given in ASTM C618. The compressive strength of HPC increased up to a 10% OPC replacement level by WGP before it starts declining. This signifies that the highest compressive strength was obtained at 10% WGP replacement level. It was also shown that adding the WTF decrease the slump flow and enhanced the compressive, splitting tensile and flexural strengths of WGP-HPC up to 1.2% and then dropped. Overall, an optimal HPC mix with 10% OPC replacement by GWP and 1.2% WTF addition outperforms all other mixes.

Keywords: High performance concrete, Mechanical properties, Waste glass powder, Waste tyre fibres.

1.0 INTRODUCTION

High performance concrete (HPC) is commonly used in the construction sector for bridges, concrete pavement, water and sewage systems, nuclear waste containment structures, runways, port and harbour facilities, and other structural applications requiring long service life and high durability. HPC offers significant economic and architectural advantages over normal conventional concrete [1]. Normal and special ingredients are used to make HPC. Chemical admixtures such as Super-plasticizer are added to reduce water content and improve the workability. Mineral admixtures are also used as partial replacement of cement to improve both strength and durability, which is achieved by using pozzolanic materials such as silica fume or any other supplementary cementing materials. Furthermore, concrete is a brittle material with poor tensile strength and strain capacity, resulting in limited crack resistance [2]. To improve such properties, fibre is introduced to concrete [3-5].

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The practice of incorporating industrial waste materials has gained tremendous attention in the field of research to develop greener and more sustainable building materials. In Nigeria, 4% of solid wastes generated are glass [6] which is disposed in the form of glass bottles from beverage factories and glass sheets from ceramics industries. On the other hand manufacturing of cement is a major source of greenhouse gas emissions. The use of WGP as a supplementary cementitious material to offset a portion of the OPC in concrete will reduce the cost, overcome the adverse effects of OPC, and utilize industrial waste, which are harmful to the environment, natural resources, etc. Also, the use of WGP as pozzolona improves several properties and serves as a pore filler in concrete. Similarly, waste tyres also constitute major amount of solid waste throughout Nigeria. Aisien et al. [7] estimated that about 15 million waste tyres are in existence in Nigeria. They further estimated that 850,000 waste tyres are added to existing quantity annually. Waste tyres are nowadays recycled to extract few raw materials that can be incorporated in concrete to enhance its mechanical and durability properties [8]. Disposal of huge quantity of glass and tyres as waste is a serious threat to the environment. To bring out the solution to this, recycling methods were adopted to reuse and assess the effects of WGP as partial replacement of cement and WTF as addition in HPC [9, 10]

Several research works reported the individual effects of WGP and WTF in concrete. Here are some few reviews stated.

Anwar [11] investigated the influence of glass powder as replacement of cement in concrete; the glass powder was varied in fraction from 0 to 50% per increment of 5% by weight of concrete. Experiments were conducted to study the compressive, splitting tensile and flexural strengths; the results proved that 5-15% glass powder content performed better than control mix. Shekhawat and Aggarwal [12] showed that there is a decline in workability with increase in glass powder content. Shilpa and Kumar [13] conducted experiments on concrete including glass powder and found that the compressive strength obtained for concrete with 20% replacement by glass powder increased with increasing curing period when compared to control concrete. Abejide, [3] and Poon et al. [14] reported that incorporation of steel fibres in concrete has been found to improve several of its properties, primarily cracking resistance, impact resistance and ductility. Iqbal et al. [15] reported the reduction in workability with addition of steel fibre.

2.0 MATERIALS AND METHODS

2.1 Materials

Ordinary Portland cement (OPC) grade 42.5 conforming to BS EN 197 [16] with a specific gravity of 3.16 as presented in table 1 was used for this study as the main binder, while waste glass powder with specific a gravity of 2.58 was used as the supplementary cementitious material.

The waste glass powder (WGP) was sourced from Kofar-ruwa, Kano-Nigeria. Transparent soda-lime waste glass were collected, washed, dried, and manually broken before being transported to a crushing mill where the glass pieces were further crushed to a powder. After that, the crushed powder was sieved through a 75µm sieve shaker. The chemical composition of OPC and WGP were determined using the X-Ray Fluorescence (XRF) analytical method at Spectra at Spectra Laboratory Services, Kaduna-Nigeria.

Waste tyre fibre (WTF) was gathered from a disposal site in Dawanau, Kano State, Nigeria. The wire was removed by burning the tyre slices to ash in a clay-bricks incinerator at Kano State School of Technology Kano-Nigeria. The incinerator was fuelled by a kerosene heater and was designed to operate at a maximum temperature of 1500°C. The burning was done at a controlled temperature of 500-600°C. The WTF extracted from waste tyre has a specific gravity of 4.48, a diameter of 1mm and were cut into50mm length.

The fine aggregate used is clean river sand collected from river Challawa in Kano State, Nigeria, with a specific gravity of 2.63. Sieve analysis was conducted in accordance with BS EN 933 [17] in order to determine the particle size distribution as well as grading limits based on BS EN 882 [18] and was classified as Zone 2 fine aggregates as shown in Figure 1.

Table 1. Chemical Composition of OPC and WGP

Oxides	OPC Composition (%)	BS EN 197-1 [16]	WGP Composition (%)	ASTM C618 [22]
SiO_2	10.773	The sum of reactive CaO and SiO_2 shall be at least 50%. The ratio of CaO to that of SiO_2 shall be at least 2%. MgO ≤ 5%. Cl ≤ 0.1 %. SO_3 ≤ 4%. LoI ≤ 5%.	69.697	The sum of reactive SiO_2, Al_2O_3 and Fe_2O_3 shall be at least 70%. The reactive SiO_2 shall not be less than 25% The CaO shall be less than 10%. SO_3 ≤ 4% LoI ≤ 10%.
Al_2O_3	1.702		0.257	
Fe_2O_3	2.877		0.252	
CaO	60.773		4.696	
MgO	0		0	
ZnO	0.004		0.001	
MnO	0.04		0.11	
SO_3	0		0	
TiO_2	0.066		0.041	
Cr_2O_3	0.012		0.011	
Cl	0		0	
LoI	6.424		4.288	
S.G	3.16		2.58	

2.2 Method

The experimental investigation was divided into two stages: assessing the impacts of partial substitution of OPC by WGP in HPC and determining the optimal percentage of WGP on one hand, on the other hand assessing the effects of WTF addition on the optimal WGP content. ACI 211.1 [23] was used to design the HPC grade 50. Table 2 shows the mixtures that were employed; the WGP was modified in fractions ranging from 0% to 25% per 5% increase by weight of OPC. The mixtures were used to test for the compressive strength of HPC and determine the optimum percentage of WGP content. WTF was then added to the optimal WGP content in increments of 0.4% by weight of OPC ranging from 0% to 2%, the mixture proportions are presented in Table 3. The slump flow, compressive, splitting tensile and flexural strengths were determined using BS EN 12350-8 [24], BS EN 12390-3 [25], BS EN 12390-6 [26] and BS EN 12390-5 [27] respectively. The specimens were cured for 3, 7, 28, 56, and 90 days, respectively. All tests were performed in three repetitions, and the average was evaluated.

3.0 RESULTS AND DISCUSSION

3.1 Physical and Chemical Analysis of the Constituents Materials

Table 1 shows the oxides composition of the OPC and WGP. The result suggests that the OPC used in this study meet the requirements of BS EN 197-1 [16] for OPC. As a result, the OPC used was of good quality in terms of chemical composition and met the regulatory standards.

Table 2: Grade 50 HPC mix proportions.

WGP Contents (%)	Cement (kg/m^3)	WGP (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Super-plasticizer (kg/m^3)
0	539.5	0	631.16	979.34	205	6.5
5	512.525	26.975	631.16	979.34	205	6.5
10	485.55	53.95	631.16	979.34	205	6.5
15	458.575	80.925	631.16	979.34	205	6.5
20	431.6	107.9	631.16	979.34	205	6.5
25	404.625	134.875	631.16	979.34	205	6.5

Table 3: Mix proportion of optimum WGP-HPC reinforced with WTF.

WTF Content (%)	WTF (kg/m3)	OPC (kg/m^3)	WGP (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
0	0	485.55	53.95	631.16	979.34	205	6.5
0.4	1.079	485.55	53.95	631.16	979.34	205	6.5
0.8	2.158	485.55	53.95	631.16	979.34	205	6.5
1.2	3.237	485.55	53.95	631.16	979.34	205	6.5
1.6	4.316	485.55	53.95	631.16	979.34	205	6.5
2.0	5.395	485.55	53.95	631.16	979.34	205	6.5

WGP has a total SiO_2, Al_2O_3, and Fe_2O_3 content of 70.206%, which is slightly higher than the minimum value of 70% recommended in ASTM C618 [17] for a suitable pozzolana and would thus be considered as a reactive pozzolana. This shows that WGP is a good pozzolanic material having satisfied the recommended limit given in

BS EN 197-1 [16] and ASTM C618 [22]. The result is consistent with the findings of Shao et al. [28] and Shi & Wu [29] on conventional concrete made with WGP.

Figure 1 depicts a distribution chart showing the particle size distribution of WGP, fine and coarse aggregates. According to the BS 882 [18] grading limits for fine aggregates, the fine aggregate falls in grading zone II. This demonstrates that medium sand outnumbers fine and coarse sand. It is coherent and well-graded, which is ideal for the production of HPC. In addition, the curve in Figure 1 shows that coarse aggregates have dominant particle sizes of 14 mm and 10 mm. This demonstrates that the aggregate size is within the stipulated limitations of a maximum of 20 mm for use in HPC as indicated by Shetty [30]. The grain sizes of WGP range from 75µm to 1.75µm. A smaller particle size of the WGP results in higher activity of glass with lime, a higher compressive strength in concrete as well as lower expansion [28].

3.2 *Properties of WTF*

The WTF have an average tensile strength of 483.33 N/mm^2, the value fall within the range of 400-1500 N/mm^2 for industry produced steel fibres for use in concrete [31]. In addition, the aspect ratio of 50 is within the range of 30-65 recommended by [32].

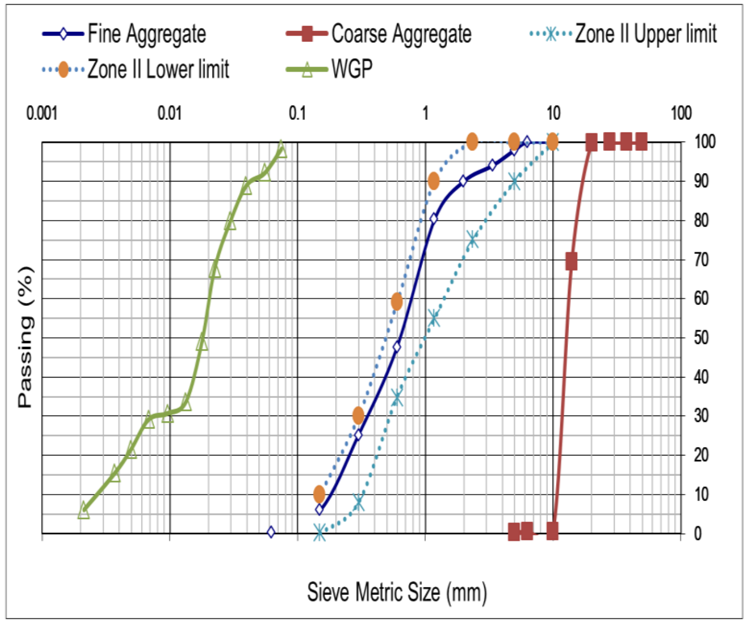

Figure 1: Particle size distribution chart of WGP, fine and coarse aggregates.

Table 4: Properties of WTF

Properties of WTF	Length (mm)	Diameter (mm)	Aspect Ratio	Tensile Strength N/mm^2
Experimental Result	50	1	50	483.33
SIKA [31]	-	-	-	400-1500
JG/T 472 [32]	20-60	0.3-1.2	30-65	-

3.3 *Slump Flow of WGP-HPC*

Figure 2 depicts the slump flow result, which shows that the slump flow values steadily decreased when the replacement amount of WGP was increased. The reduced workability could be attributed to WGP's increased reactivity and surface area when compared to OPC. It could also be attributed to an increase in water demand caused by an increase in WGP content, which increases the surface area of glass particles and the amount of angular shaped glass particles in the mix, resulting in less fluidity [12].

Metwally [33] and Afif et al. [34] reported similar patterns in slump flow levels. All the samples examined satisfied the requirement of BS EN 12350-8 [24] for slump flow value of 550-850mm.

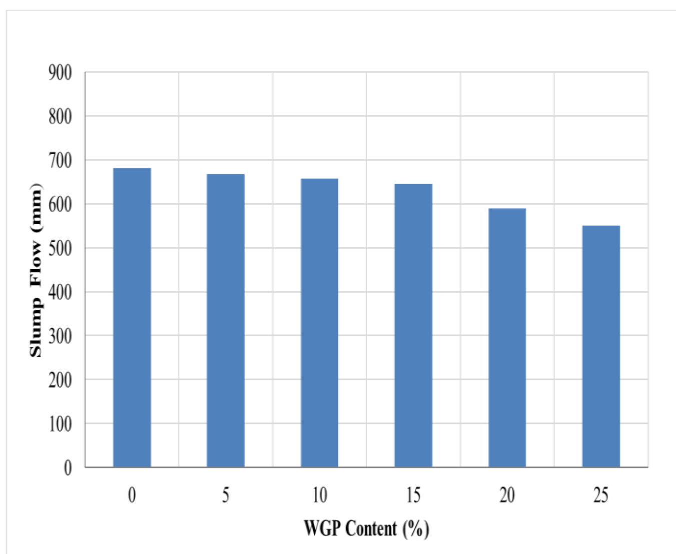

Figure 2: Slump flow WGP-HPC

3.4 *Effects of WGP on Compressive Strength of HPC*

Figure 3 depicts the compressive strength test results of WGP-HPC. The results reveal a gain in compressive strength with a continuous increase in WGP at 5% and 10% and a progressive decrease at 15%, 20%, and 25% OPC replacement levels. There was also a rise in compressive strength with increasing curing age at all replacement levels. The increase in compressive strength with curing time could be attributed to WGP's micro filling ability and pozzolanic activity.

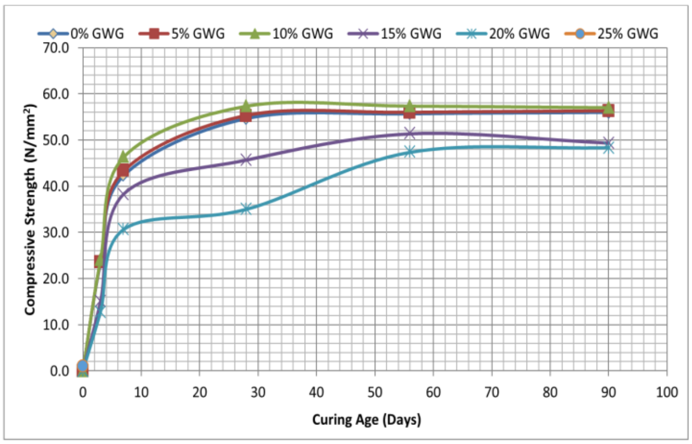

Figure 3. Compressive Strength of WGP-HPC.

However, after 10% WGP concentration, a drop in compressive strength was found. In this case, the amount of silica available in the hydrated cement matrix is most likely too high, and the amount of produced C-S-H is most likely insufficient to react with all of the available silica. As a result, the dilution effect of OPC and weaker formation of C-S-H gel due to the pozzolanic reaction takes over, and the strength begins to decrease, which is consistent with previous work on pozzolanic reaction by Ogork and Uche [35]; Ogork and Auwal [36] and Lalitha et al. [37] worked on groundnut husk ash (GHA), corn cob ash (CCA) and WGP respectively. Thus, it can be concluded that 10% is the optimum level for replacement of cement with WGP. The optimal dosage is consistent with Lalitha et al., [37] and Kumarappan [38] who used glass powder as a partial replacement for OPC.

3.5 *Effects WTF on Slump Flow of WGP-HPC*

As illustrated in Figure 4, the slump flow data indicate that the workability of WGP-HPC decreases as WTF addition increases. The inclusion of WTF has a considerable impact on the workability of WGP-HPC, making the WGP-HPC stiff and lowering the flowability of WGP-HPC. The decrease in workability might be attributed to the uneven distribution of WTF in the WGP-HPC, their interaction with the OPC matrix, and the ability of the concrete to be properly cast or sprayed, which increases the void content and decreases workability [15]. The outcome is in line with the findings of Brown and Atkinson [9] and Nehdi et al. [39].

However, the mix remained adequately workable, which can be attributed to the presence of the superplasticizer which have the tendency of deflocculating cement grains and increase in the fluidity, as well as induced electrostatic repulsion between particles, dispersion of cement grains and consequent release of water trapped within cement flocks [40].

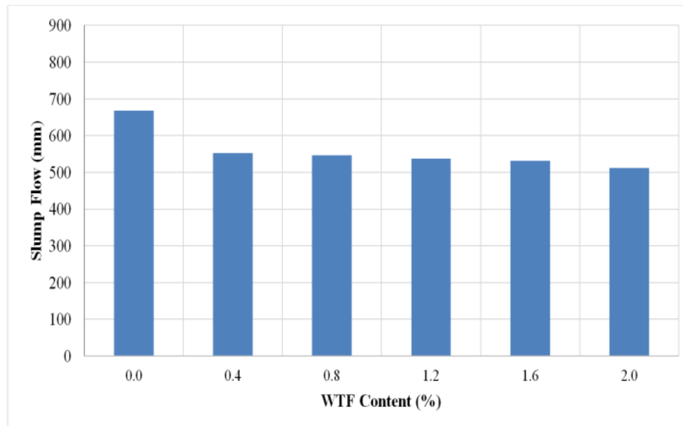

Figure 4. Slump flow of WTF-WGP-HPC

3.6 *Effects of WTF on Strength of WGP-HPC*

A. *Compressive strength*

Figure 5 depicts the compressive strength of WGP-HPC reinforced with WTF. The results show that compressive strength rises with curing age at all WTF addition levels, although only significantly with WTF addition up to 1.2%, and declines with higher WTF content beyond 1.2%. The 28-day compressive strength of WTF-WGP-HPC ranged from 55.7-57.3N/mm^2 for 0.0-1.2% WTF content and decreased to 56.7 and 54.3N/mm^2 for 1.6 and 2.0% WTF content, respectively.

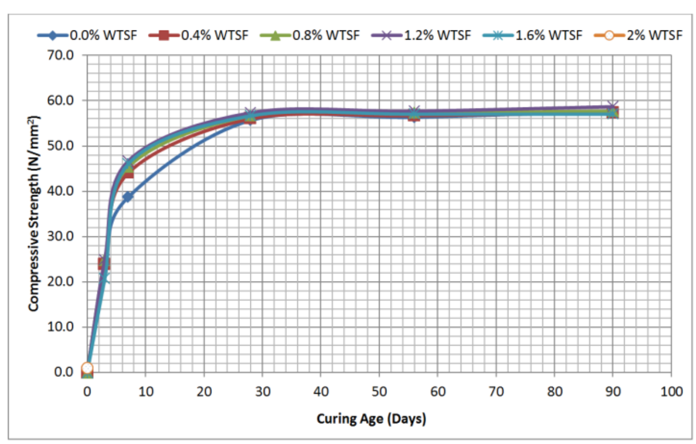

Figure 5. Compressive Strength of WTF-WPG-HPC.

The improved compressive strength could be attributed to the WTF's ability to withstand and produce stress on the concrete matrix as a result of greater bond strength between fibres in WGP-HPC [41]. It could also be owing to WTF's ability to delay the unstable formation of micro cracks while also restricting the spread of these micro cracks and the composite effect for concrete and steel fibers under load [8]. As the WTF addition increases to 1.6% and 2.0%, the fibers tends to agglomerate, serving as points of stress concentration. The agglomerate fibers create void spaces resulting in weak spots that reduce the compressive strength of WGP-HPC [42, 43]. As a result, 1.2% was determined to be the optimal percentage addition of WTF in WGP-HPC. The optimal percentage composition of WTF is lower than the percentages obtained by Sugathan [44] and Isyaka and Ogork [45] which are 2% and 1.5 respectively.

B. Splitting tensile strength

The splitting tensile strength of WGP-HPC reinforced with WTF is presented in Figure 6. The results indicate that the splitting tensile strength increased significantly with increase in percentage addition of WTF dosage up to 1.2% and there was reduction in splitting tensile strength with further increase in percentage fibre content. The increase in splitting tensile strength with increase in WTF content may be attributed to the effect of the crack resistance and the pull-out force of WTF on the bond strength of WGP-HPC [10]. It could also be due to increase in toughness and the energy absorption capacity of the WTF in WGP-HPC, as the fibres take effect as soon as cracks begin to develop due to the applied load thereby providing post crack ductility which is evident from the test result when compared with the control, consistent with the findings of Garrick [46].

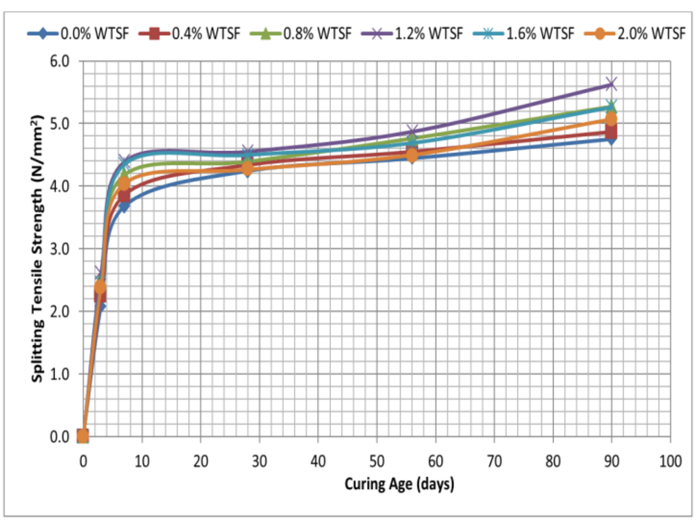

Figure 6. Splitting Tensile Strength of WTF-WGP-HPC.

The increase in 28 days splitting tensile strength ranges from 4.2N/mm^2 for control sample to 4.6N/mm^2 for 1.2% WTF content, the splitting tensile strength declines to 4.5N/mm^2 and 4.3N/mm^2 for 1.6% and 2.0% respectively. The void spaces generated by agglomerated fibres may be the reason for the loss in splitting strength, resulting in weak areas that reduce the splitting tensile strength of WGP-HPC [43]. The results also indicated that the splitting tensile strength of WTF-WGP-HPC at all percentage fibre addition was higher than that of control samples at all curing ages. This could be because steel fibres act as reinforcement in concrete, allowing the concrete specimen to exhibit substantial deformations while enduring high post-cracking stresses [5].

C. Flexural strength

The flexural strength of WGP-HPC reinforced with WTF increased with increase in curing age and with increase in WTF content as shown in Figure 7. The increase in flexural strength could be due to the delay in the occurrence of micro cracks in cement matrix, the fibres resist the propagation of cracks and tend to reduce the sudden failure of specimen, which causes an increase in the load carrying capacity of concrete [4, 47]. It may also be attributed to the effect of the tensile strength of the fibre and the pull-out force of fibre on the bond strength of WGP-HPC reinforced WTF [10].

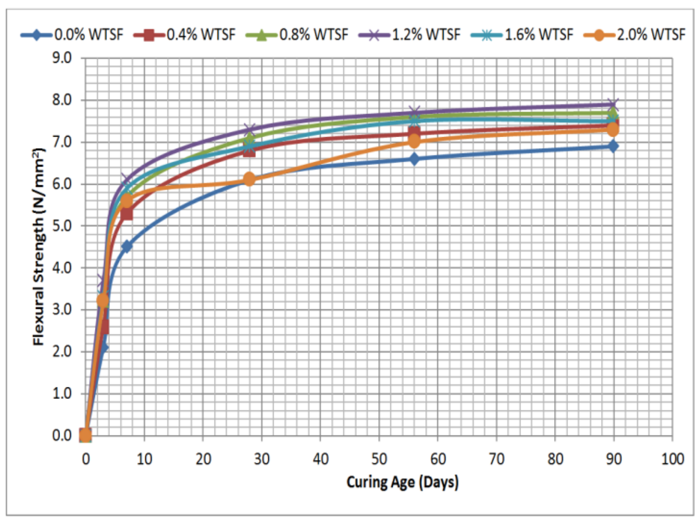

Figure 7. Flexural Strength of WTF-WGP-HPC.

However, the results also indicated that the flexural strength of WTF-WGP-HPC at all percentage fibre addition was higher than that of control samples at all curing ages. This could be because WTF acts as reinforcement in concrete, allowing the concrete specimen to exhibit enormous deformations while resisting high post-cracking stresses [5].

4.0 CONCLUSION

The study yielded the following conclusions:

i. The soda lime WGP is suitable material for use as a pozzolana since it satisfies the requirement by having a combined SiO_2 + $Al2O_3$ + Fe_2O_3 of more than 70%.

ii. The workability of HPC reduces as percentages of WGP and WTF increases.

iii. HPC containing 10% WGP exhibited greater strengths properties at all curing age. As such WGP can be used as a supplementary cementing material in HPC. Similarly, WTF addition of up to 1.2% can enhance strength properties of WGP-HPC at all curing age.

iv. The optimum replacement level of WGP for OPC and WTF addition in HPC is 10% and 1.2% respectively.

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